OPERATING INSTRUCTIONS

FOR

MILLIVAC METER

MODEL MV-18C

TEST EQUIPMENT CALIBRATION
BRANCH
A.E.E.L. - N.A.D.C.

MILLIVAC INSTRUMENT CORPORATION
P. O. Box 997, Schenectady, N. Y.

OPERATING INSTRUCTIONS FOR THE MILLIVAC TYPE MV-18c VACUUM TUBE MILLIVOLTMETER (RF)

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IN ORDER TO AVOID MISUNDERSTANDINGS concerning the proper use of this unusual instrument, its calibration and its response to non-sinusoidal wave shapes a careful study of the following instructions is recommended.

Do not judge, nor re-calibrate this valuable instrument without first having read its instruction book in full detail. You will find it well worth your while.

W. D. Volkers

President,
Millivac Instrument
Corporation

TEST EQUIPMENT CALIBRATION
BRANCH
A.E.E.L. - N.A.D.C.

OPERATING INSTRUCTIONS II-99-A

Millivac Type MV-18C RF Voltmeter

General Information:

The MV-18 C vacuum tube voltmeter by itself, without RF probes, is a highly sensitive millivoltmeter for DC. This instrument can be used for three basically different kinds of measurements:

a) DC Millivoltmeter: The right switch, marked "DC-mV" provides 3 measuring ranges, 10 mV, 2.5 mV and 1.0 mV full scale. Each range is being operated at MIDZERO, positive voltages reading to the right and negative voltages to the left. The right switch also acts as a general Function Switch. In its upright position, marked "Off" it disconnects the meter's power supply from the AC line. In its left position, marked "RF-mV, Use Left Switch" it connects the meter for RF voltage measurements as described below.

b) RF VOLTMETER: As an RF voltmeter the MV-18 C uses 3 types of germanium rectifier probes. They are probe A, AA and B. Their circuits are described in bulletin B-206 which is attached to this instruction book. Each probe contains a IN34 crystal, a coupling and peaking condenser between the probe-tip and the crystal and a 1.5 megohm DC filter resistor. The probe converts the incoming RF voltage into a DC voltage which is fed into the MV-18 C meter. The left switch on the panel of the MV-18 C, marked "RF Volts", acts as a calibrated voltage divider, breaking down the DC voltage developed by the germanium crystal in such manner that definite calibrated RF measuring ranges are provided.

c) Thermocouple Meter: The MV-18 C can be used for directly proportionate measurements of the RF input voltage of ordinary RF vacuum thermocouples and the new Pseudo-Thermocouples, manufactured by Millivac Instrument Corp. Such measurements can be carried out on the instrument's 1 mV, 2.5 mV or 10 mV ranges by turning the right switch to the particular range desired and setting the meter's pointer to zero on the square law scale on top of the dial.

Accessories:

The MV-18 C meter is furnished with a shielded probe-lead, a short 2-pole clip lead for DC measurements and our standard type A probe for RF measurements up to 2.5V. The short DC clip-lead fits into the same female amphenol connector which holds the RF probe. In addition to the standard type A probe, which is supplied with each instrument, other probes are available on special order. Full details are given in our price list and bulletin B-206, attached to these instructions.

1) Operation of the MV-18 C as a DC Millivolt Meter:

Plug shielded lead into input socket on panel and short clip lead into other end of shielded lead. Short input by clipping red clip to black clip. Set right switch to 10 mV range. Turn "Mid-Zero" (or UPSCALE ZERO) control

clockwise until pointer reaches Mid-Zero position. Now open shorted input leads and connect to DC source whose voltage is measured. This source should have less than 100,000 ohms input impedance and should have less than 10% AC hum, otherwise mid-zero setting with shorted clips is incorrect with reference to actual DC voltage-measurement.

Switch on the meter's "Polarity Pulse" on the right side at the bottom of the panel. This pulse adds every second a small positive DC voltage to the voltage being measured. If the needle kicks to the right this means that the meter is not overloading and that the measurement is "right". If it kicks to the left it means that the meter is being overloaded by a negative input voltage and that the measurement is "wrong". After checking whether or not the meter is overloading turn off the polarity pulse.

If the meter is overloading (positively or negatively) on its 10 mV Mid-Zero range this indicates that the voltage to be measured is higher than 10 mV and therefore beyond the DC-reach of the instrument. On the other hand, if the reading is so small or so near to Mid-Zero that a larger deflection of the pointer is desired repeat measurements on the 2.5 and 1.0 mV scales. However, make sure that before each reading the pointer is reset to Mid-Zero by shorting the input terminals as described and adjusting the UPSCALE (or Mid-Zero) control.

The DC millivolt measuring ranges of the MV-18 C are limited to measurements between approximately 100 microvolts and 10 mV. For higher voltages we recommend our MV-17 C DC voltmeter which covers a total range between 100 microvolts and 1,000 volts, or the MV-27 C which has a range of 25 microvolts to 1,000 volts.

NOTE: PREVENT MEASURING ERRORS BY REPEATEDLY SWITCHING ON THE POLARITY PULSE WHICH REVEALS NEGATIVE OVERLOADING.

2) RF Millivolt and Volt Measurements:

Make sure that UPSCALE (or Mid-Zero) control is completely switched off. Also switch off Polarity Pulse. Select RF probe as follows:

For RF voltage measurements between 10 mV and 2.5 Volts plug type **A** probe into shielded lead.

For RF voltage measurements between 2.5V and 1,000 Volts use B probe.

For RF voltage measurements between 100 mV and 25 Volts the AA probe is optional. It has a smaller input loading capacitance than the A probe and therefore is preferred against the A probe whenever minimum circuit loading is vital and extreme sensitivity not needed.

There is a dividing line between the 2.5 V and 10 V ranges on the RF-Volts switch. On its left side use probes A and AA, on the right side probe B. Using the wrong probe or using the wrong side of the dividing line will give incorrect readings. To avoid burning out crystals, do not use probes above their rated values. In the event of crystal burnouts, return damaged probe to Millivac Instrument Corporation for repair.

3) RMS and Peak Measurements:

When making RF measurements with germanium crystal probes down to voltage

levels as low as 10 mV or even less the user should bear in mind that below 100 mV these probes actually measure RMS values and above 1 V half-wave peak values. Between 100 mV and 1 V readings there is a transition from RMS to peak measurements. This difference between actual measurements does not influence readings if signal-waves are perfectly sinusoidal.

Millivac probes are calibrated with perfectly sinusoidal signal waves. Therefore any measurements of signal waves which are strictly sinusoidal will be correct over the whole range from 10 mV up beyond 1 V. On the other hand, non-sinusoidal wave shapes may create considerable calibration discrepancies.

Important:

WHEN MEASURING PURELY SINUSOIDAL VOLTAGES NO CONSIDERATION NEED BE GIVEN TO THE FACT THAT MILLIVAC PROBES (LIKE ALL CRYSTAL RECTIFIER PROBES) MEASURE RMS VALUES BELOW A CERTAIN VOLTAGE THRESHOLD AND PEAK VALUES ABOVE ANOTHER THRESHOLD, AS DESCRIBED.

4) RF-Scales:

The meter has 4 RF scales which are calibrated, as follows:

The top scale is used for all voltage ranges above 250 mV, except 10 V and 25 V. The next lower scale is used for 250 mV (probe A) and 25 V (probe B) only. The one below is calibrated for 100 mV (Probe A) and 10 V (Probe B) full scale. And the lowest scale is used for 25 mV Probe A only.

The attached bulletin B-206 contains all pertinent information with regard to RF frequency response and circuit loading features of the MV-18 C meter.

5) Pseudo-Thermocouple Measurements:

Bulletin B-206, attached to this instruction book, also gives a detailed description of pseudo-thermocouples and their applications. It contains a typical calibration chart for such a PTC (Fig. 2)

The principal difference between probe measurements and PTC measurements lies in their calibration. While the MV-18 C, when used with any of its probes, A, AA or B, is a regular calibrated high-frequency voltmeter, having 10 separate ranges between 25 mV and 1,000 V full scale, it is a basically non-calibrated RF galvanometer, when used with thermo-couples of the regular heater type or with Millivac pseudo-thermocouples. For accurate measurements individual calibration of a given PTC at a given frequency with a given MV-18 C meter is recommended. For less accurate measurements (within approximately 10% full scale accuracy) the calibration chart in Fig. 2 of B-206 may be used.

PTC millivolt-measurements may be carried out on the 1 mV, 2.5 mV and 10 mV DC ranges of the instrument, either at mid-zero or at square-law zero. After having plugged the PTC into the meter's shielded extension lead turn the UPSCALE or mid-zero control clock-wise until the needle reaches zero on either the square-law or the mid-zero scales. The PTC converts RF voltages, fed into it, into positive DC voltages which will drive the pointer upscale.

On the meter's 1 mV DC scale RF voltages as low as 1 mV can be observed. Approximately 10 mV will be found to drive the pointer to full scale on the square-law dial.

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6) DC Calibration Check:

When checking the DC-calibration of the MV-18 C proceed as follows:

a) Switch meter to 1 mV DC range, short input terminals (black & red clips), switch off both up-scale zero control and polarity pulse and observe noise reading. It should be less than 10% of full scale. If it is higher this would indicate faulty tubes, a faulty power-supply or a noisy DC-modulator.

b) Check 10 mV (mid-zero) calibration, using standard-cell potentiometer or equivalent. Source impedance must be less than 100 K.

c) Check 2.5 mV (mid-zero) calibration in same manner.

d) Check 1 mV (mid-zero) calibration.

7) RF-Calibration Check:

Before attempting to check the RF calibration of the MV-18 C meter make sure that reliable RF calibration standards are available.

The average signal generator which is in commercial use today is a device which is designed to hold extremely high accuracy frequency-wise but has much less accuracy as far as wave shapes are concerned and a very poor accuracy indeed as far as voltage calibration is concerned. 80% of the MV-18 C meters which we have supplied are used for the purpose of monitoring the output of signal generators.

The reason why signal-generator voltage calibrations are usually not very accurate and cannot be is this:

The voltmeter in a signal generator is usually electrically located at the end of a transmission line inside the generator while the output terminals are located at the end of another external transmission line (with or without pad). The output is further subjected to the calibration hazards created by the calibrated attenuator. To assume that the voltage calibration at the end of a transmission line, following a hazardous divider and feeding the signal into a complex load, must be accurate, because the voltmeter on the panel of the signal generator gives a certain reading, would be about equivalent to the assumption that the voltage across the power plug of a refrigerator is correct because the voltmeter in the municipal power station reads what it should read.

The greatest hazard, however, is loading at the consumer's end of the signal generator's transmission line. A few uuf shunting capacity can upset calibrations considerably, often characteristic load impedances are not correct or have undergone changes and many other hazards are continuously threatening voltage calibration accuracy of a signal generator by itself.

After having shipped approximately 2,000 of these MV-18A, B or C Voltmeters, we have received approximately 15 complaints regarding calibration of these meters. In all these cases we have been able to track the complaint down to a misunderstanding on our customer's side of signal generator accuracy. We found that in all these cases the complaining customers had placed their full confidence in the voltage calibration of their signal generators and were surprised to hear that signal generators can be off in their voltage calibrations as much

as 10, 20, and occasionally even 50%, as we have often verified it.

For further enlightment on the subject of high-frequency voltage calibrations a reprint of a paper, "Conclusive Voltage Calibration of High Frequency Signals", is enclosed.

DO NOT MISJUDGE AND DO NOT SPOIL THE CALIBRATION OF A VALUABLE INSTRUMENT BEFORE BEING ABSOLUTELY SURE THAT THE STANDARD USED FOR COMPARISON IS RELIABLE AS FAR AS SINUSOIDAL WAVE-SHAPE, ACCURATE ATTENUATION, FREEDOM FROM TRANSMISSION LINE MISMATCHING ETC. IS CONCERNED.

8) Re-Calibrations, General Information:

Before attempting to re-calibrate the RF ranges of the MV-18 C meter, its DC ranges should be checked and re-calibrated, if necessary. This procedure is of great importance because DC calibration directly influences RF calibration.

9) Re-Calibration of DC Ranges:

Follow the procedure outlined in chapter 6 which describes how to set up equipment for, and how to perform DC calibration checks.

In order to calibrate the DC ranges use the 3 amplifier gain controls in the back of the meter which individually adjust the gain on the 10 mV, 2.5 mV and 1 mV mid-zero ranges. When adjusting these controls it is always necessary to re-set mid-zero after which the effect of the re-setting upon calibration should be checked. The 3 d.c. calibration controls do not influence each other.

10) Re-Calibration of RF Ranges:

There is a calibration panel underneath the amplifier in the back of the meter. It contains 5 screw-driver-operated, properly marked potentiometers. They individually influence the calibration of the following RF ranges:

100 mV	(A Probe)
250 mV	(A Probe)
1 V	(A Probe)
2.5 V	(A Probe)
1 KV	(B Probe)

It will be noted that no individual controls are provided for the 2.5 mV, 10 V, 25 V, 100 V and 250 V ranges. The 25 mV range is automatically calibrated through proper calibration of the 10 mV DC range. If a minor correction should be found to be desirable, a compromise can be established by setting the 10 mV DC range either slightly higher or slightly lower to "split the difference" against minor calibration errors of the 25 mV RF range.

The 10 V range (B Probe only) is automatically calibrated by calibration of the 100 mV (A Probe) range. If these 2 ranges should not line up perfectly, the capacitive divider in the B probe should be adjusted so that the 10 V range matches the 100 mV range perfectly. In the same fashion, the 25 V range is automatically calibrated through calibration of the 250 mV range, the 100 V range through calibration of

the 1 V range and the 250 V range through calibration of the 2.5 V range. Again it may be found desirable to strike a certain compromise setting of the capacitive divider in the B probe. This divider is screw-driver-operated and can be reached without opeing the B probe.

The AA Probe should be used on all ranges which are designated for the A probe. Readings should be multiplied by 10 since the adjustable capactive divider in the AA Probe has a ratio of 1:10. This divider should be reset only after perfect calibration of the A probe has been completed.

A, AA AND B PROBES ARE INDIVIDUALLY CALIBRATED FOR THEIR OWN METERS AND BEAR EACH METER'S SERIAL NUMBER. THEY CANNOT BE INTERCHANGED WITHOUT RE-CALIBRATION AND THEREFORE SHOULD NOT BE INTERCHANGED.

11) PTC-Calibration:

The pseudo-thermocouples, while originally intended to be used in uncalibrated fashion, can now also be used with an individual "calibration cord", type CL-112, available upon special order. This cord contains an adjustable potentiometer which makes it possible to calibrate accurately an individual pseudo-thermocouple so that the MV-18 C reads exactly "100" on the square law dial when the RF input voltage is exactly 10 mV. This latest improvement, available upon special order only, now provides the possibility of operating a MV-18 C meter with a perfectly calibrated 0-10 mV range.

12) RF Frequency Response:

Full information is contained in bulletin B-206 forming part of this instruction book (see figure 4). For highest accuracy at frequencies above 200 MC, individual calibration with a reliable signal source is recommended.

13) General Description of DC Meter Circuit:

The MV-18 C uses a completely stable carrier-type DC amplifier which does not contain bridge circuits and therefore, for all practical purposes, is free from zero drifts and the necessity of repeated zero adjustments. A "shunting contact" type DC modulator converts DC voltages into 120 cycles. The modulator should never be opened or tampered with since this automatically cancels the instrument's one-year guarantee.

A complete circuit diagram is attached.

The instrument has two range switches, the "RF VOLTS" switch and the "DC mV's" switch. The "RF volts" switch handles all ranges between 25 mV and 1000 V RF full scale. The remaining three lowest ranges (10 mV, 2.5 mV and 1 mV DC full scale) are handled by the "LOW-mV's" switch which feeds the incoming DC signal directly into the modulator but varies the carrier amplifier's gain. On the 10 mV range it is 20%, on the 2.5 mV range it is 40% and on the 1 mV range it is 100% of its maximum gain. All 3, the 10 mV, 2.5 mV and the 1 mV range are operated at mid-scale zero in order to "preload" the carrier amplifier's output rectifier. This lowers the instrument's "minimum observable deflection" to less than 100 microvolts and makes it more valuable as a hypersensitive DC null detector and RF millivoltmeter.

The carrier amplifier used in this instrument has a so-called "starved" input tube (6J7) which operates at reduced plate current (0.02 mA) and has an exceptionally large load-resistor (16 meg.). This increases its gain to 1,000 or more. The second stage is directly coupled to the first. It is not starved and has a gain of 200, bringing the total gain of the first two stages to 200,000. The starved amplifier in this case amplifies the carrier signal produced by a DC modulator having less than 10 microvolts noise at 11 megohms input impedance. The negative feedback ratio on the most sensitive scale of this voltmeter is roughly 100 to 1, and on the less sensitive scales 1,000 to 1. With such high feedback rates, tube noise and hum are negligible.

The MV-18 C measures positive and negative DC voltages in a forward direction. This eliminates the necessity of either switching leads or operating a reversing switch. However, the polarity of the voltage being measured can be determined by switching on the meter's "Polarity Pulse". This is a slowly beating neon-oscillator which every two seconds adds a small positive DC voltage in the measuring circuit. If the pointer periodically kicks to the right the polarity is plus, if it kicks to the left it is minus.

The meter has a 4" x 2" rectangular dial with 6 scales. They are the main scales covering all measuring ranges between 25 mV and 1000 V RF full scale, two special mid-zero scales for the 10 mV, 2.5 mV and 1 mV ranges, and a square-law scale. The latter is mainly for RF--RMS measurements with theremocouples. It facilitates conversion of DC readings into RF values. Its zero is raised to 20% of full scale in order to "preload" the output rectifier which makes the meter more sensitive at very low input voltages.

14) Guaranty:

The MV-18 C (meter proper, without probes) is guaranteed for one year after date of shipment from the factory to customer against defective parts and workmanship. A guarantee card, properly signed, is enclosed with each meter. Keep this card in your files. Do not, under any circumstances, return a meter, believed to be defective, to our factory without first taking the following steps:

1. READ THE FOREGOING INSTRUCTIONS CAREFULLY including bulletin B-206 in the back of the booklet.

2. MAKE SURE THAT THE UNUSUAL FEATURES OF THIS METER ARE FULLY UNDERSTOOD.

3. When making RF Volts measurements with probes make sure that the UPZERO or mid-zero control is completely turned off and that the polarity pulse is turned off.

4. When measuring small DC voltages make sure that the meter is not overloading by checking its performance with the Polarity Pulse, as explained above.

5. Check meter mechanically, for broken parts and dis-located modulator, due to transport shock.

6. Protect probes and pseudo-thermocouples against damage by excessive voltages. In many cases troubles can be traced to damaged probes. Keep a spare set of probes on hand for checking and reference purposes.

7. Recalibrate RF ranges when necessary.

8. Recalibrate DC ranges of meter only if you are sure that readings are more than 3% off. This will rarely be found to be the case.

9. DO NOT OPEN MODULATOR AS THIS AUTOMATICALLY CANCELS GUARANTEE.

10. If steps described above should fail to produce desired result write to us, care of SERVICE DEPARTMENT, describing exact trouble. Wait for authorization to send in meter. When sending it make sure to enclose exact return address and shipping instructions. All shipments must be prepaid.

MILLIVAC INSTRUMENT CORP.

Engineering Department

PARTS LIST FOR MV-18 C

RESISTORS

R1-16 Meg
R2-43 K
R3-130 ohm
R4-4.7 Meg
R5-4.7 Meg
R6-390 K
R7-15 K
R8-51 K adj
R9-1.6 Meg
R10-4.7 Meg
R11-300 K, 1 W
R12-16 K adj
R13-15 K
R14-7.5 K adj
R15-24 K, 1 W
R16-1 K, 1 W
R17-4.7 Meg
R18-1.1 Meg
R19-.47 ohm
R20-7.5 K
R21-160 K
R22-68 K
R23-50 K
R24-50 K
R25-50 K
R26-30 K
R27-100 K
R28-1.2 Meg, 1 W
R29-200 K
R30-3 Meg,Cont.
R31-750 K
R32-510 K
R33-40 Meg
R34-75 ohm
R35-15 Meg
R36-4.50 Meg*
R37-3.19 Meg*
R38-510 ohm
R39-24 K
R40-8.2 K
R41-39 K
R42-180 K
R43-30 K
R44-240 K
R45-1 K, Cont.
R46-10 K, Cont.
R47-10 K, Cont.
R48-50 K, Cont.
R49-100 K, Cont.
R50-220 K
R51-4.7 K, 1 W
R52-18 Meg

NOTE: VALUES MARKED BY * ARE PRECISION PLUS MINUS 1%

CONDENSERS

C1-100 MF, 50 V
C2-.05 MF
C3-.0005 MF
C4-.1 MF
C5-8 MF, 150 V
C6-.05 MF
C7-.05 MF
C8-.5 MF
C9-20 MF, 450 V
C10-20 MF, 450 V
C11-.1 MF, 600 V
C12-.01 MF
C13-.05 MF
C14-40 MF, 450 V
C15-40 MF, 450 V

CIRCUIT CHANGES, after May 1, 1954 (Change from MV-18B to C).

A) New Calibration Circuit:

R38: Replaced with 1k pot. and 510 ohm resistor in series.

R39: Replaced with 10k pot. and 24k resistor in series.

R40: Replaced with 10k pot. and 8.2k resistor in series.

R41: Replaced with 50k pot. and 40k resistor in series.

R42: Replaced with 100k pot. and 180k resistor in series.

R44: Replaced with 250k resistor.

B) Power Supply Changes:

Stancor P-6010 transformer replaced by P-8406.

R19 removed and .47 ohm resistor in series with modulator excitation.

4.7 k, 1 W resistor in transformer center tap lead.

C) Shielded input lead is now equipped with ground clip wire, in accordance with majority wishes of customers. However, great precaution should be taken to avoid measuring errors due to reactive drops in this ground wire, when making measurements at frequencies higher than 30 mc.

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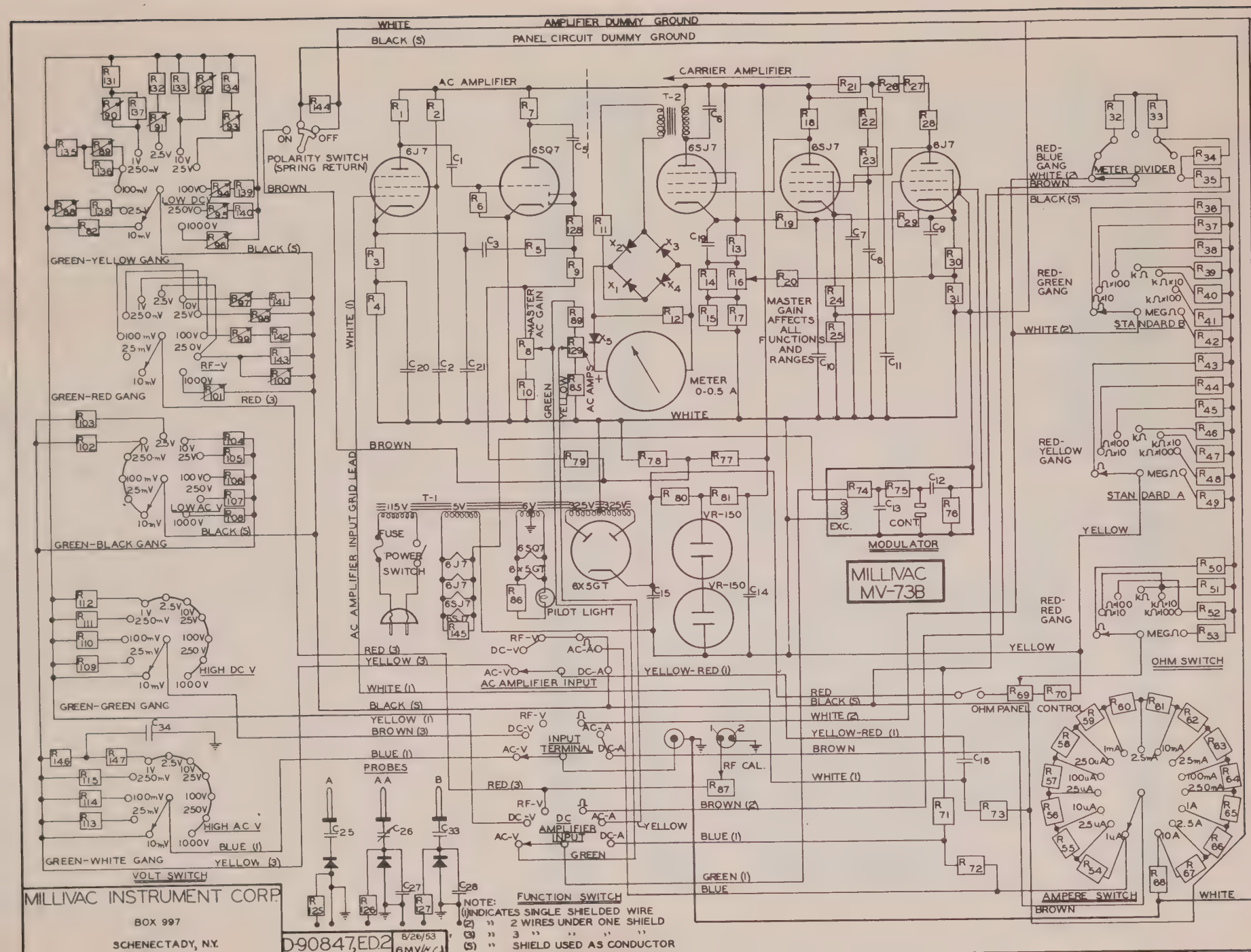
Engineering Department.



MILLIVAC INSTRUMENT CORP.

BOX 997

SCHENECTADY, N.Y.

D-90847, ED2 8/26/53 6MV/KC

MILLIVAC VACUUM TUBE MILLIVOLT METER FOR HIGH FREQUENCIES

MODEL MV-18C

Features:

- Measures RF signals down to a single mV and DC down to 50 microvolts.
- Wide Frequency Range (1 MC to 200 MC flat within 10% directly calibrated. Useful up to 2,500 MC with calibration chart).
- Minimum Circuit Loading (new "MINIMUM CAPACITY PROBES" have 1.0, 1.5 and 2.8 MMF rated input capacities).
- Wide Voltage Range (RF 10 mV to 1,000 V, directly calibrated, 1 mV to 10 mV by chart— DC 50 microvolts to 10 mV, directly calibrated).
- Square Law Dial For Vacuum Thermocouples and High Impedance "Pseudo-Thermocouple" Measurements.
- Complete RF, Oscillator and IF Signal Tracing Through TV and FM Receivers.
- DC Grid Current Measurements Down to 10^{-11} A.

Fig. 1 MV-18C Meter with Probes

TIME PROGRESSES, SO DO WE

GENERAL:

Below the input voltage level of 25 mV germanium diodes and other crystal rectifiers are nearly square law detectors. When combined with a high impedance vacuum tube millivoltmeter for DC, having 1 mV full scale deflection at 6 megohms input impedance, these crystal rectifiers can be used as "pseudo-thermocouples" for high impedance millivolt measurements at input wattage levels substantially lower (microwatts) than those of ordinary heater type thermocouples (milliwatts). This is particularly useful for mV measurements above 5 MC since little in the way of instruments has been available in those higher frequency ranges, so far.

The new Millivac MV-18C RF millivoltmeter fills the inportant gap between highly sensitive low frequency meters (AC-amplifier-type-meters) and less sensitive high frequency meters (vacuum-tube-diode-probe-followed-by-a-low-gain-DC-amplifier type meters). It is the first high frequency vacuum tube voltmeter which combines high sensitivity and high frequency response.

DESCRIPTION:

The MV-18C is the first vacuum tube voltmeter for high-impedance millivolt measurements above 5 MC. Its design has been made possible by combining a carrier-type high-impedance DC vacuum-tube millivoltmeter (having 6 megohms input impedance and 1 mV full-scale deflection) with a new type of thermocouple, having substantially higher input impedance and higher sensitivity than the conventional vacuum thermocouple. This new "pseudo-thermocouple" is essentially a germanium rectifier diode operated at unconventionally low input-voltage levels (down to 1 mV). At these low levels the DC output-voltage of the germanium crystal is closely proportionate to the square of the RF input voltage in much the same manner in which the DC output of a vacuum thermocouple follows a square law. The MV-18C, at input voltage levels between 1 mV and 10 mV, is, therefore, a RF-thermocouple-meter of unusual sensitivity, excelling ordinary thermocouple meters by its high input impedance (50,000 to 150,000 ohms and 1 to 3 MMF compared to the 5 to 50 ohms heater resistance of vacuum thermocouples) as well as by its nearly flat frequency response up to 200 MC (heater loops and heater resonances being avoided). At these low voltage levels readings are taken on the 1 mV DC dial, a calibration chart (Fig. 2) being used for conversion of readings into RF millivolts. They may also be taken on the instrument's square-law dial which facilitates such conversion.

For RF voltage measurements above 10 millivolts and up to 1000 volts, 3 additional germanium diode probes are available which make it possible to read these voltages directly on the meter's 4 calibrated RF dials. Ten separate switch ranges are provided for this purpose, the lowest being 0-25 mV, the highest 0-1 kv.

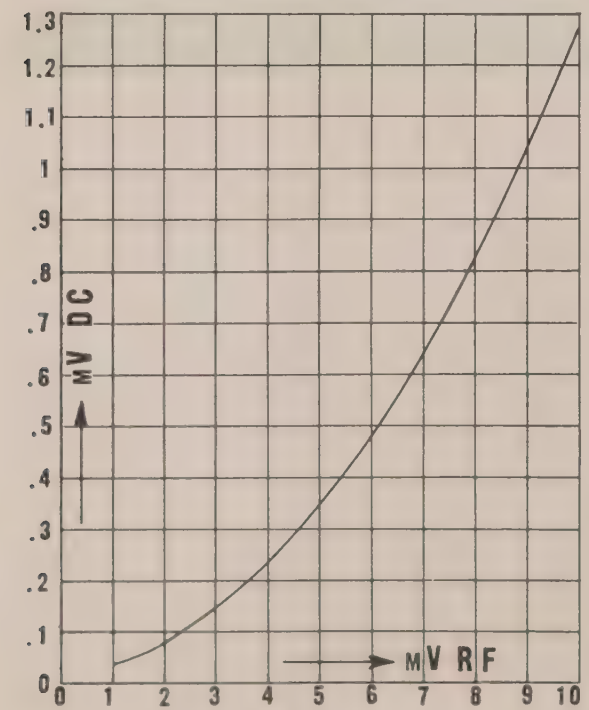


Fig 2
Pseudo - Thermocouple Calibration Chart

MINIMUM CIRCUIT LOADING:

The MV-18C has 3 calibrated RF probes (types A, AA and B) having different capacitive input dividers and sensitivities. The circuits of these probes are shown in Fig. 3.

Probe A, in its latest "MINIMUM CAPACITY" form, has a rated input capacity of only 1.0 MMF plus-minus 25%. Such exceptionally low circuit loading was made possible by reducing crystal shielding to the very minimum and by housing both the RF and the DC filter components of the probe in a generously spaced polystyrene head. The probe is designed so that all conducting elements between tip and crystal, including the flat plates of the coupling condenser, are in a straight line. This keeps the probe free from resonance at high and ultra-high frequencies. The RF voltage leaves the probe as rectified DC through a 1.5 megohm filter resistor. The measuring range of this probe is 10 mV to 2.5 V.

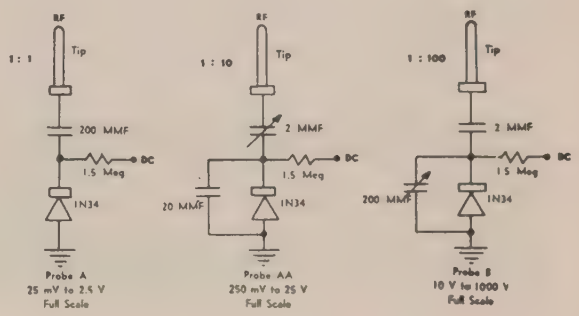


Fig 3 - Circuits of A, AA & B Probes

Probes AA and B are equipped with 1:10 and 1:100 capacitive voltage dividers. These two "extra" probes which are not supplied with the instrument unless specially ordered cover the RF voltage range between 2.5 volts and 1,000 volts. The input capacity of the AA probe is 1.5 MMF plus-minus 25%, its individual voltage range between 2.5 volts and 1,000 volts. A nameplate on the probe-shell states that readings are taken on the 25 mV to 2.5 V ranges of the meter and should be multiplied by 10. The B probe has 2.8 MMF rated input capacity, also with 25% tolerance. It covers voltages between 10 V and 1 kV and has its own meter ranges, no multiplication of readings being required.

RF FREQUENCY RESPONSE:

Fig. 4 shows the frequency response of the MV-18C when used with either a pseudo-thermocouple or any of its three-calibrated RF probes. The curve is completely flat up to 30 MC where it begins to decline, reaching—4% at 100 MC. At

CONCLUSIVE VOLTAGE CALIBRATION OF HIGH FREQUENCY SIGNALS

BY

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Abstract.—The calibration of high frequency voltages, particularly at low levels, is a subject of considerable controversy. The author describes calibration methods which he considers "conclusive" because they do not rely on accuracy claims made by other manufacturers for ac calibration equipment, such as signal generators, bolometers and thermocouples. Considering the voltage of a standard cell a reliable calibration reference, the paper shows how the final goal of accurate low-level, high-frequency calibration is reached by rectification of accurate sine-wave signals. From accurate dc measurements the method progresses to reliable high voltage low frequency, high voltage high frequency, low voltage low frequency and low voltage high frequency calibrations. Calibration hazards are eliminated in step-by-step fashion, either by "conclusive" physical proof or by "consistency" tests. These involve a number of parallel group-tests using dissimilar equipment to determine the "range of agreement" between measurements made with such varying equipment. Consistency of measurements in this range is then considered conclusive proof of accuracy.

I. INTRODUCTION

The methods used by the Millivac Instrument Corporation for calibration of high frequency signals are considered "conclusive" because they do not rely on accuracy claims for ac calibration equipment made by other manufacturers. They are based on standard cells, *i.e.*, on accurate dc voltages. They do not rely on any of the many commercially available high frequency standards.

This policy of caution was born a few years ago when the company developed and placed on the market its model MV-18A, the first sensitive untuned millivoltmeter for frequencies above five megacycles. This instrument made it possible, for the first time, to measure lowlevel signals down to a single millivolt at frequencies above five megacycles. Soon, however, it was discovered that the calibration at low voltage levels often did not agree too well, and in some cases disagreed quite drastically, with the calibration of high frequency signal generators regardless of their make or price.

Whenever such a discrepancy exists it is only natural for the user of a brand-new instrument to doubt the new equipment and to put more faith into his older gear, which he may have used for years, never seeing any reason to question its reliability. The firm establishment of the MV-18B meter in the minds of our customers as a reliable measuring device for low voltages at high frequencies, therefore, was bound to take some time. However, the instrument has now reached a degree of acceptance such that many users prefer to monitor the operation of signal generators at low levels by actual measurement of their output, rather than relying upon the calibration of the generator and its output dividers, transmission lines, and pads, which may introduce major errors.

II. CRITICAL SURVEY OF CALIBRATION TOOLS

The calibration of high frequency signals requires a reliable coordination with accurately calibrated low frequency signals or dc.

When setting up our calibration procedure, it was soon realized that low-level

calibration of high frequency signals is subject to certain basic hazards which must be avoided. We entirely ruled out as calibrating tools both thermocouples and bolometers because we did not want to rely on assurances of their manufacturers concerning their frequency response without knowing how these manufacturers had obtained such information. The skin-effect, dielectric losses, unavoidable loop reactances and loop resonances are but a few of the hazards to which these devices are subject when used interchangeably at high and at low frequencies or at dc. Without conclusive assurance that at all frequencies involved, all, or at least exactly the same percentage of energy reaches the thermo-junction or bolometer element we could not possibly accept these devices as reliable calibration tools.

III. DIODES AS RECTIFIERS AT HIGH VOLTAGE LEVELS

On the other hand, we found that reliable calibration, not only at high voltage levels, but also at lower levels can definitely be obtained at practically all frequencies, up into thousands of megacycles, by rectification. There are, admittedly, certain hazards present here too. They are less severe at high levels. The most important of these include capacitive shunting, contact potentials, transit time within the tube at high frequencies, transmission line effects at high frequencies resulting in standing waves, and other effects which may lead to amplitude changes between the point of measurement and the point of rectification. Up to certain frequency limits they can practically always be rendered harmless by proper layout. But more important is the fact that there are available certain conclusive tests which rule out the existence, or prove the successful elimination, of such phenomena.

For instance, we may test a vacuum diode rectifier at a low frequency (30 cps) for rectification errors due to its inherent contact potential with reliable ac standards such as the dynamometer. A measurement of the dc output of the diode (diagram at bottom, Fig. 1) with an accurate dc compensator and a sensitive, high impedance VTVM may show (left side, Fig. 1) a dc output of 1.25 volts due to contact potential. At three volts ac input we may find that the dc output voltage is only 20 millivolts higher than the theoretical values of $\sqrt{2}$ times the ac value, assuming, of course, perfectly sinusoidal wave shapes. At 10 volts the error may be only 5 millivolts, which would be 0.05 percent. If after these tests we draw the conclusion that with an input signal of 100 volts the dc error cannot possibly be more than 5 millivolts, which was the error found at 10 volts, we would have a percentage error of not more than 0.005 percent. This error is based on a conclusion, not an actual measurement. But we should feel free to draw this obvious and conservative conclusion because we fully understand the nature of the physical phenomenon, contact potential, and its decreasing influence with increasing signal levels. It so happens that, in this case, we can also verify our conclusion by comparing our ac rectification measurement with a direct dynamometric ac voltage measurement.

In other cases we cannot verify our conclusions by direct measurements. Then we have to rely on consistency tests to prove our assumptions. Again, the simple vacuum diode offers a good example to illustrate this point. Although we may assume that its frequency response is completely flat up to a certain frequency, say 300 megacycles, because we feel certain that standing waves, inductive voltage drops, resonant drops, and other phenomena which could create signal amplitude differences between the point of measurement and the point of rectification cannot occur, we obviously should

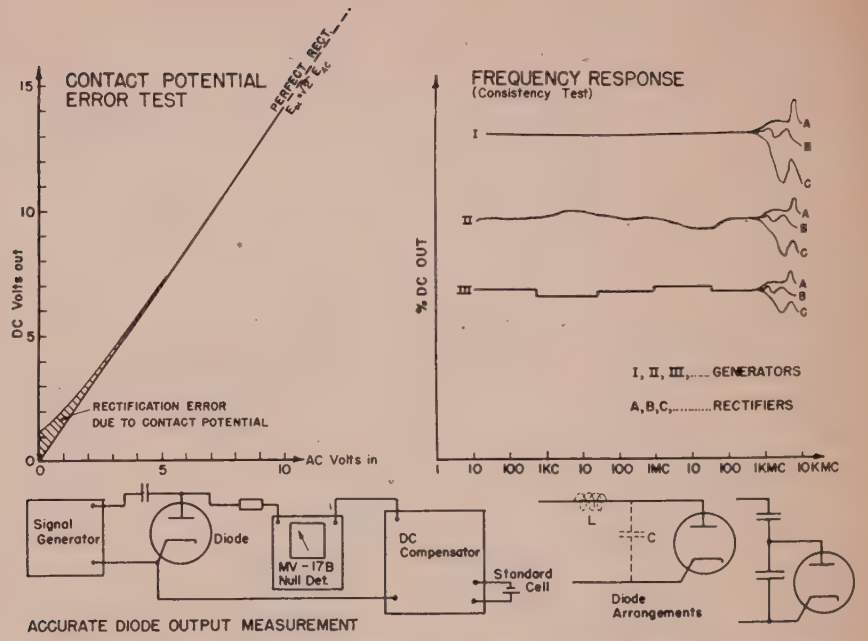


Fig. 1—Calibration hazards of vacuum diodes. Left: Contact potential. Right: Frequency response. Bottom: Calibration circuit.

not take responsibility for our calibrations until, and unless, we have at least shown to our own satisfaction at which frequencies such disturbing phenomena occur. The quickest and most convincing manner in which such an analysis can be carried out is a group of consistency tests which use several dissimilar diodes and diode-circuits fed from one or more "blind" signal generators (right side of Fig. 1).

Blind signal generators are either sweep-generators or steady generators whose outputs are kept as constant as possible over the entire range, without our relying on their output meters or on their manufacturer's assurance of output-constancy.

The diodes used in such a consistency test should vary among themselves as much as possible in their physical structures. Some should be fed directly, others through capacitive dividers. Some should be connected through extra-long transmission lines with and without extra inductance and capacitive loading. With our various generators and these widely varying diodes we will then obtain several sets of response curves, such as those on the right side of Fig. 1. They all agree closely up to a certain frequency, in this instance 300 to 350 megacycles, and then show major disagreements. We may safely assume that these disagreements are caused by one or more of the hazards just mentioned. But we may also safely conclude that all our diodes are free from these hazards within the frequency range in which they agree.

The slight up and down curvatures and steps within the "agreement" regions of the two lower groups are caused by minor calibration errors and range-switching among the calibrated generators. The top group actually represents several uncalibrated, overlapping generators which were specially built. They acted as one unit in conjunction with an MV-18B meter and several crystal-rectifier probes to cover the entire

frequency range. Incidentally, we cannot claim any extra distinction for showing such a perfectly flat calibration curve below 300 megacycles, because all measurements in the top set are based on our own crystal-frequency-response measurements. In other words, we are here checking Millivac against Millivac. Important, however, is that again the three diode rectifiers agree among themselves below 300 megacycles.

IV. DIODES AS RECTIFIERS AT LOW VOLTAGE LEVELS

A radically different situation exists when we want to use diodes to measure high frequency signals at low levels in the millivolt region. Here the vacuum diode is almost ruled out because its contact potentials assume such large relative proportions that their error-creating interference is difficult to eliminate. Naturally we therefore turn to crystal diodes. At low voltage levels they have a much higher rectification efficiency than vacuum diodes. Unfortunately, however, they also have two serious calibrations hazards of their own which we must eliminate or rule out. These are the gradual transition from linear to square-law rectification (Fig. 2, left) with decreasing voltage, and a steady decline of the crystal output at higher frequencies (Fig. 2, right).

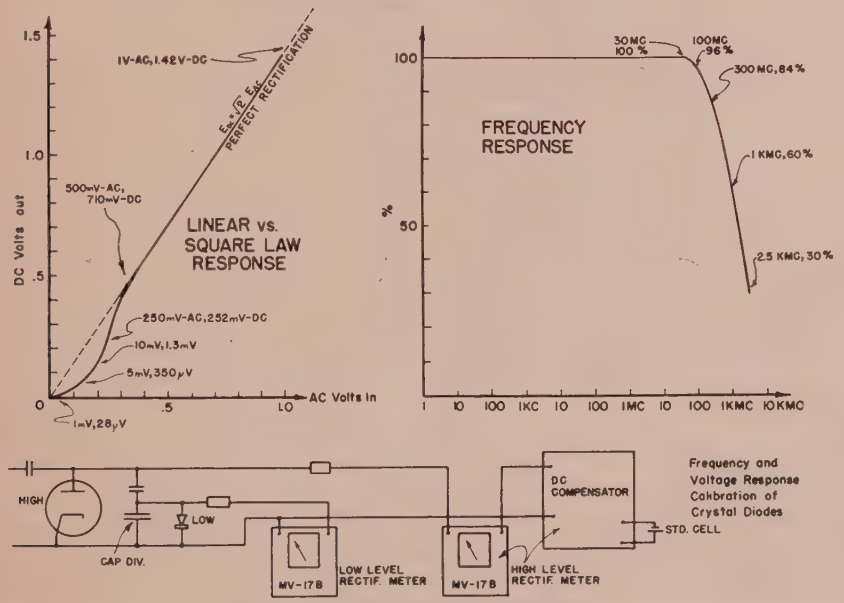


Fig. 2—Calibration hazards of crystal diodes. Left: Change from linear to square-law response. Right: Declining response above 30 mc. Bottom: Calibration circuit.

The general shape of the dc output *vs.* ac input curve shown in Fig. 2 (left) is typical of all semi-conductors, including silicon. It is typical of the operation of these diodes as unloaded or nearly unloaded rectifiers. When loading the crystals heavily, their output characteristic follows a different, more linear pattern. The curve was obtained with a high impedance dc millivoltmeter (MV-17B) which is capable of following the rectification properties of crystal diodes down to an ac input level

of one millivolt. At one volt ac input we have 1.42 volts dc output, or roughly $\sqrt{2}$ times the ac voltage, as we would expect with perfect rectification. At 500 millivolts we still have perfect rectification; however, if we reduce the ac voltage to 250 millivolts, we do not get $\sqrt{2}$ times this value in dc but only approximately 250 millivolts. As we reach lower ac levels, the rectification deteriorates very rapidly. At 10 millivolts input we generate only 1.3 millivolts dc, at 5 millivolts input only 350 microvolts dc and at one millivolt ac input we have only 28 microvolts dc. In other words, with one millivolt input our rectification efficiency is the ratio of 28 microvolts over the expected 1.42 millivolts dc or only two percent. But the dc millivoltmeter is sensitive enough to measure this small voltage with a crystal loading of 6 megohms. At these low levels we do not have true rectification in our crystals. Their forward and back resistances, when measured on a low-voltage bridge, are identical. DC voltages are, as far as we know, produced by a thermo-electric effect, with germanium and its impurities or "doping" ingredients acting as a thermo-junction. We therefore call these crystals, operating at low levels, "pseudo-thermocouples."

The other hazard with which all crystal diodes are afflicted is the steadily dropping frequency response at frequencies beyond approximately 30 megacycles (Fig. 2, right side). Germanium crystals of the contact diode type vary little in this respect. The curve shown is true within ten percent for all crystals that have come to our attention, whether operated at high voltage levels or at low voltage levels. Some typical response values are entered on the curve. At 100 megacycles we are four percent down, at 300 megacycles we have an output of 84 percent or 16 percent down, at 1000 megacycles the output is 60 percent or 40 percent down, and at 2,500 megacycles our output is only 30 percent, which means that we are 70 percent down. At this time we do not have available reliable measurements beyond this frequency limit.

There are various explanations of the high frequency output decline. A simple, though perhaps somewhat crude explanation, is the inherent *RC* configuration of the crystal terminals and the semi-conductor between them. In spite of the severe hazards which crystal diodes show when operated over exceptionally wide input-voltage and frequency ranges, we can perform surprisingly reliable calibrations with them over wide ranges. Accuracies of better than one percent can be obtained.

At the bottom of Fig. 2 is a calibration circuit which eliminates both hazards of the crystal diode. It consists of a high level vacuum diode rectifier and a capacitive divider. Its low voltage section feeds the crystal diode. The input voltage of the vacuum diode is calibrated by means of a dc compensator and an MV-17B null-indicator in a manner already described. The output of the crystal is then measured directly with a specially calibrated MV-17B meter, giving us approximately one percent accuracy. Or, if higher accuracy is desired, a second dc compensator may be used together with an MV-17B null-indicator.

In our analysis we have already cleared the vacuum diode as a reliable calibration tool at sufficiently high voltage levels, for instance, 100 volts. If we can also clear the capacitive divider, we are in a position to calibrate reliably the crystal diode at low and very low levels over a frequency range not only including and below 30 megacycles where the response is flat, but also through the higher frequency section of the curve where the output drops off rapidly.

V. DIVIDER HAZARDS

The left side of Fig. 3 shows how we can eliminate two typical capacitive-divider

hazards. As in the case of the vacuum diode, we have the possibility of standing waves and line inductances, and also condenser inductance and condenser resonance. Most of these calibration disturbances can actually be avoided by careful design. Condensers with straight, short leads and flat plates, such as mica condensers, or with concentric electrodes such as the bushing or shielded conductor type can be selected or designed to be entirely free from non-linear reactance *vs.* frequency up to frequencies well above 2,500 megacycles.

But to rely on pure design features would not be conclusive, nor responsible. More reliable and conclusive are, again, consistency tests. If we provide several capacitive dividers with wide physical variations, and if we find that our calibrations agree within a certain "consistent" frequency range as shown on the left side of Fig. 3, then it is permissible once more to conclude that resonances, inductive drops, standing waves, *etc.*, do not occur within this range. On the other hand, the fact that considerable deviations are found at higher frequencies outside this range is additional and conclusive proof that our reasoning and our testing method is based on sound physical conceptions

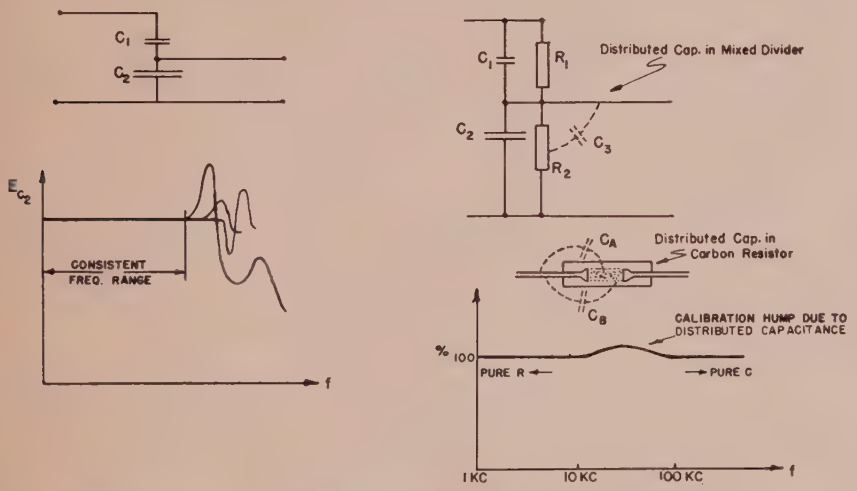


Fig. 3—Divider hazards. Left: "Consistent" frequency range of capacitive dividers. Right: Distributed capacitance in mixed RC dividers.

VI. DISTRIBUTED CAPACITANCE

A further hazard in calibration work with dividers is distributed capacitance in mixed resistance and capacitive dividers, shown on the right side of Fig. 3. In our calibration equipment we carefully avoid such "mixed" dividers or "capacitively corrected resistance dividers", as they are often called, because the phenomenon of distributed capacitance inevitably creates measuring errors which cannot be neglected. Distributed capacitance, as indicated by the dotted condenser, C_3, on the right side of Fig. 3 is the effect of shunting stray capacitances between the terminals of a resistor and portions of the resistance element. The effect can occur in a pair of series resistors or in a single resistor. It can never be completely avoided, not even by elaborate shielding, because it involves the active element of the resistor itself. Only purely

capacitive dividers should therefore be used for accurate calibration of high frequency signals. Careful impedance calculations, confirmed by tests, conclusively establish the lower frequency limits of capacitive dividers. Being aware of the phenomenon of distributed capacitance, we use only purely capacitive dividers for high frequency calibration and purely ohmic dividers for low frequency calibration. A comfortable overlapping range, roughly between two kc and 20 kc, enables us to compare accurately and calibrate these two types of dividers.

Although our company avoids mixed ohmic and capacitive dividers in calibration equipment where highest accuracy is needed, it considers these parallel *RC* dividers a necessary evil in range-switching in ac voltmeters. Frequency ranges here are too wide for purely ohmic or purely capacitive dividers. But by careful design we have, so far, been able to keep the typical broad distributed capacitance hump (right lower corner of Fig. 3) to well below two percent. The occurrence of such humps is a common experience in wideband amplifiers, oscilloscopes and vacuum-tube voltmeters. They occur mostly somewhere between 10 kc and 200 kc.

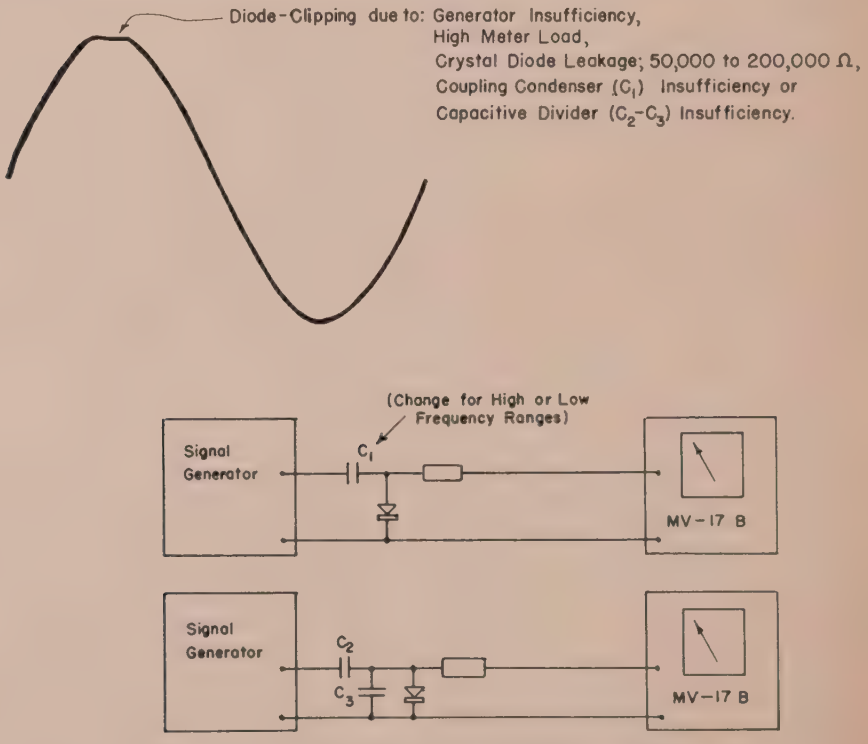


Fig. 4—Diode loading hazard creating miscalibration by clipping.

VII. GENERATOR AND RECTIFIER LOADING HAZARDS

Figure 4 shows two further basic calibration hazards which we must avoid when measuring ac signals by rectification. On the left side of Fig. 4 is shown a sine-wave

signal which is slightly clipped due to generator-insufficiency or excessive loading in the measuring circuit. Assuming again half-wave rectification with a peaking condenser, the clipping occurs only in one half cycle, either above or below the zero line. Fairly large calibration errors can, of course, be created by such clipping. To avoid them we must make sure that our generators have reasonably low output impedance which may be assured by heavy capacitive loading. As far as the measuring circuit load is concerned, it is often difficult to avoid heavy loading, particularly if crystal rectifiers are used. We found that the ordinary germanium contact-type diode usually has a "leakage resistance" between 50,000 and 200,000 ohms. We call "leakage resistance" the forward or back resistance of a diode at near-zero voltage. We measure it by energizing a Wheatstone Bridge with an exceptionally small battery voltage, for instance, 10 millivolts. At such a low operating level there is practically no difference between the forward and back resistance.

If we therefore have to expect a substantial leakage such as 50,000 ohms in a contact crystal diode (or, for that matter, only a few hundred ohms in a junction type diode) we must make sure that our charging condenser C_1 is large enough to hold the voltage between rectification charging pulses and that our generator is "stiff" enough to deliver these pulses.

Conclusive proof of the absence of clipping is simple enough by oscilloscope observation. If we are out of the frequency range of an oscilloscope preamplifier, we may have to conduct tests at a sufficiently low frequency to make observation possible. And as we go to higher frequencies our generator and our coupling condenser C_1 automatically "stiffen up" particularly, if the generator is heavily capacitively loaded. A similar loading hazard exists if we do not feed the crystal directly from the generator but through a capacitive divider as shown near the bottom of Fig. 4.

In our calibrations with crystal rectifiers over a wide frequency range we usually exchange coupling condensers according to frequency. For instance, if our frequency is 60 cycles we make C_1 at least 2 microfarad, also C_3 in the lower divider circuit. On the other hand, if the frequency is 10 megacycles, these condensers are only 100 to 300 micromicrofarads. We found that it is unwise to use excessively large condensers, not warranted by impedance requirements, because such oversize condensers have a tendency to be inductive or to resonate when used at frequencies beyond their normal range of application.

VIII. DISTORTION ANALYSIS

The accuracy of ac signal calibration by rectification, especially half wave rectification, is greatly influenced by wave shapes. Distortion measurements are usually based on rms or average values. Since we are actually measuring peaks it is obvious that a seemingly small distortion of a sine wave, such as two percent (often found in commercial signal generators) can create measuring errors substantially larger than two percent. We therefore not only build our own signal generators to assure minimum wave distortion, but also use our own method of distortion analysis which we feel is more conclusive than simply to rely upon the usual equipment for distortion or harmonic measurements. Figure 5 shows a signal generator feeding an output filter which emphasizes harmonics and suppresses fundamentals. A three-stage *RC* filter is used in which impedances in each subsequent stage are 10 times higher than in the preceding stage. This simplifies calculations of the output amplitude reproduction ratio between the fundamental and its 3rd, 5th and

other harmonics. We can quickly and accurately calculate this ratio for a single filter stage as shown in Fig. 5 (lower right). Since the loading of each preceding stage by each subsequent stage can be neglected, this value can simply be raised to the power of the number of filter stages, here the 3rd power. We can either feed the output of this harmonic-emphasizing-filter into a distortion-analyzer or into an oscilloscope or both. Minor harmonic contents of our generator wave on the left (Fig. 5) clearly appear greatly exaggerated on the right. The exaggeration rate can be accurately calculated for each harmonic. For instance, if the third is predominant and if we measure five percent, and if the calculated exaggeration of our 3rd harmonic is 1000, then our actual distortion would be only 0.005 percent.

Figure 5 also illustrates two other methods of distortion analysis which are less convenient and accurate but which are sometimes necessary for wave shape analysis, particularly at very high frequencies. One consists of simply tuning a receiver to the harmonics of the signal and measuring the output with one of our crystal probe type high frequency millivoltmeters. The other is a purely defensive approach which is old and often used, namely excessive *RC* filtering of the signal before using it. Again we can calculate the rate of harmonic-reduction in our signal by the formula shown in Fig. 5 (lower left).

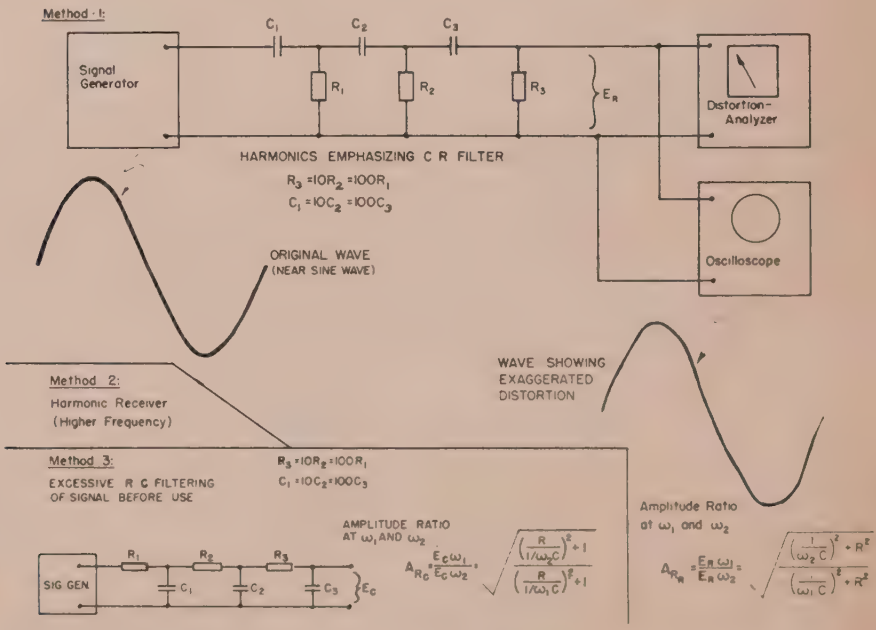


Fig. 5.—Assurance of perfect sinusoidal wave shapes. (Method 1) Harmonic-Emphasizing filter for analysis. (Method 2) Harmonic receiver. (Method 3) Harmonic suppression for wave-shape improvement.

IX. THREE-DIMENSIONAL CALIBRATION

When calibrating ac voltmeters it is advisable to divide all calibration operations into three major and basic groups; range-to-range low frequency calibration, low

frequency scale distribution and frequency response over the entire frequency range. A good example to illustrate this method is the calibration of the Millivac MV-12A low frequency meter having a frequency range of 20 cycles to 250 kilocycles and a voltage range of 0.7 millivolt to 1000 volts.

Figure 6 shows a 3-coordinate-system, *X*, *Y*, *Z*. It represents the three basic steps or directions forming our three-dimensional calibration. In direction *X*, we calibrate the instrument at low frequencies, actually 90 cycles per second, with a low distortion signal generator. We adjust the ohmic dividers on the instrument panel until the meter reads exactly full-scale on all its 11 ranges from 3 millivolts full-scale up to 1000 volts full-scale. Each range has its own calibration-potentiometer.

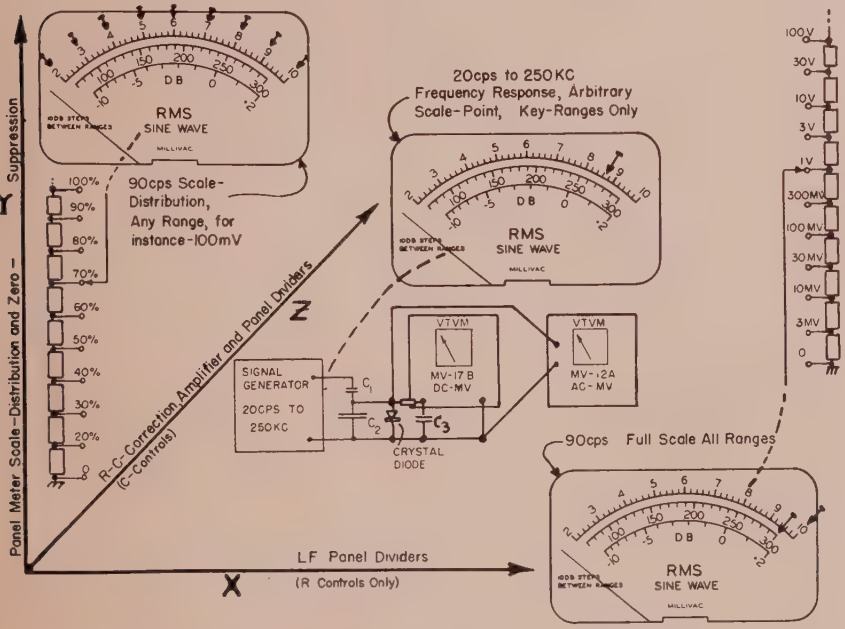


Fig. 6—Three-dimensional calibration: Scale-to-scale lf, scale-distribution lf and lf-hf response.

The next step in the *Y*-direction checks and corrects on a single range the scale distribution and zero suppression of the panel meter at nine scale-points between 20 and 100 percent of full scale. The calibration frequency is again 90 cycles per second.

Finally, in the Z-dimension we adjust the capacitive dividers of the instrument for frequency response on a few "key" ranges. These are ranges where such adjustment is either possible or necessary. We use a specially built signal generator for 20 cycles to 250 kilocycles. Excellent wave shapes are again assured. We rectify and measure our signals with a crystal diode preceded by purely resistive or purely capacitive dividers according to frequency range. Actually we do not calibrate accurately the output of the diodes, but we note the reading of our MV-17B dc millivoltmeter at an arbitrarily chosen scale point, and an arbitrary low-frequency at which we are completely certain that the capacitive dividers are inactive. This frequency can be

60, 400, or even 2000 cycles per second. After having set the instrument to the arbitrarily chosen scale point at low frequency, we note the corresponding arbitrary indication of the MV-17B meter. Then we raise the frequency to the upper end of the range of the instrument, 250 kilocycles. Since we are certain that the frequency response of our crystal diode is completely flat between 20 cycles and 250 kilocycles we can now use our former arbitrary indication of the MV-17B meter as a reference to assure identical amplitudes at 250 kilocycles and at the earlier low frequency. In other words, we do not rely on a proper calibration of the MV-17B dc millivoltmeter at all. Even if it were 50 percent off it would still provide us with an accurate reference between the high and the low frequency amplitudes in which we are interested.

We adjust the capacitive dividers in our ac voltmeter and check our frequency response in the same manner at several other key frequencies (150, 80 and 30 kilocycles) which, in our experience, are the most critical response points where the danger of distributed capacitance in our mixed *RC* dividers is particularly acute. If we find a hump in our response of more than 1.5 percent we correct it by dressing leads and components. Actually the occurrence of large humps is rare in this instrument.

X. CIRCUIT OF MV-12A METER

Figure 7 shows the circuit of this voltmeter, particularly its "key ranges" where capacitive dividers are used. The amplifier is divided into two sections, a three-stage pre-amplifier and a main amplifier. The three-stage pre-amplifier can best be described as a "super-cathode-follower" having a higher reproduction accuracy than the ordinary single-stage-cathode-follower due to higher gain and more feedback. The output impedance of this pre-amplifier is only 1000 ohms. It is represented by a divider-chain of calibration controls from which the signal is passed on to the main amplifier, which also has three-stages. The main amplifier has heavy negative feedback to assure calibration-permanence and good frequency response. No peaking coils are used in it, nor needed, to correct its frequency response. However, a small trimmer condenser is provided to compensate for capacitive losses in the meter leads of the full wave output rectifier circuit. The capacitive dividers, and capacitive corrections, mentioned before, are located between the directly-fed low ranges, 3 millivolt to 1 volt, 3 and 10-volt ranges, also the 30 to 300-volt ranges and the 1000-volt range.

Calibration of this instrument is very simple, because it has individual resistive and capacitive calibrating controls. An important feature of this meter is that it does not contain a single precision resistor. Precision resistors create basic inaccuracies. One percent resistors, when used in single-stage dividers, can create up to two percent range-to-range calibration errors. By having individually adjustable high quality potentiometers in our measuring circuit we can calibrate the instrument to nearly zero range-to-range error. This gives us a good headstart towards later minor calibration deviations which may develop in daily use but should not cause the instrument to be out of tolerance.

XI. LOW DISTORTION GENERATORS

Figure 8 shows the basic circuit of the 90-cycle signal generator which we use for low frequency calibrations. It is an *RC* tuned generator but it differs from other such *RC* devices by relying less on increasing signal distortion with increasing ampli-

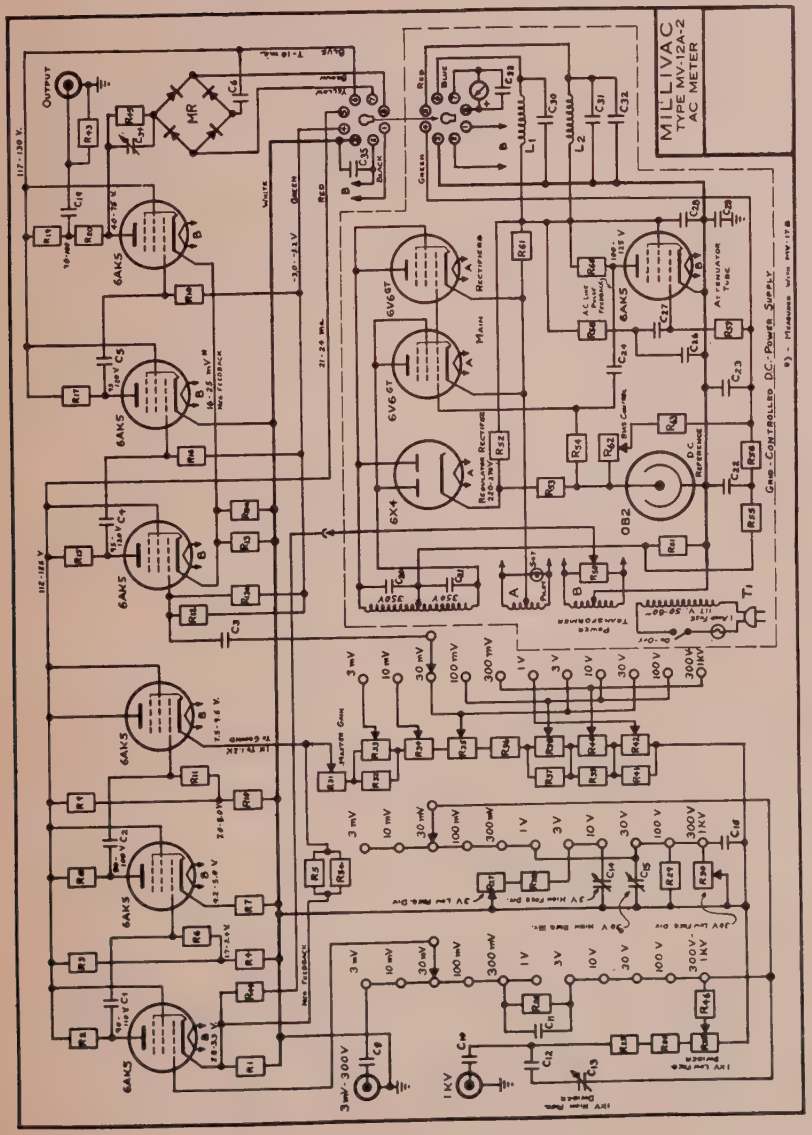


Fig. 7—Circuit of ac voltmeter calibrated by method shown in Fig. 6. Voltage Range: 0.7 mv to 1,000 v, frequency range 20 cps to 250 kc.

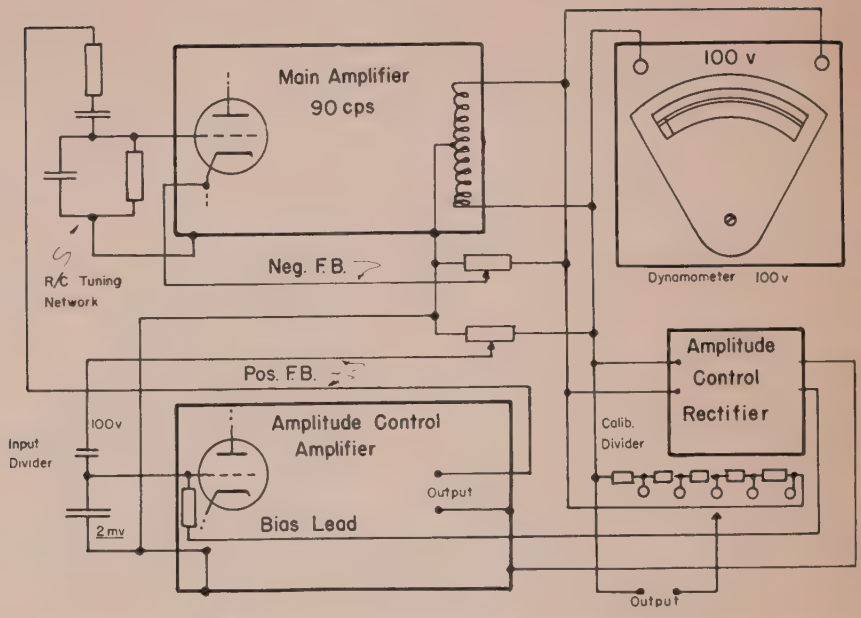
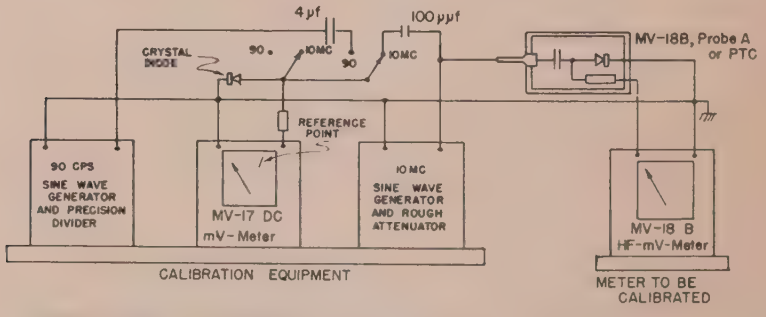


Fig. 8—Basic circuit of low distortion 90 cps generator using auxiliary amplitude control amplifier.



Accuracy Check by Independent Calibration Method.
High Level Rectification and Precision Cap. Divider.

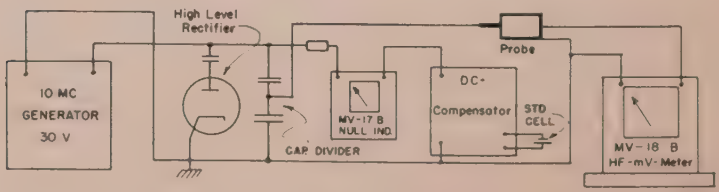


Fig. 9—Ninety cps-10 mc rectifier transfer method used for calibration of high frequency millivoltmeter shown in Fig. 10.

tude to establish a balance between positive and negative feedback. It does not use non-linear resistors (such as lamp filaments) to smooth out this amplitude-balancing distortion. Instead, we take our high level output signal, 100 volts, and rectify it to operate the bias circuit of a special amplitude control amplifier, shown in Fig. 8. It has an input-divider which feeds a small sample, of the order of two millivolts, of the main amplifier's large signal into the biased input tube. By allowing only such a very small signal to pass through the input tube, not only a remote cut-off tube, but even a sharp cut-off tube will provide excellent distortion-free amplitude-controlling action. The distortion of this amplifier is less than 0.005 percent.

XII. CALIBRATION OF A HIGH FREQUENCY MILLIVOLTMETER

When calibrating high frequency millivoltmeters such as the MV-18B, having a frequency range of 1 megacycle to 2,500 megacycles, we use a system differing somewhat from our low frequency instrument calibration. We use the equipment shown in the upper part of Fig. 9 and make occasional checks of the accuracy of the method with the equipment shown in the lower part of Fig. 9. Both methods agree within approximately one percent of full scale which gives us great confidence in either of them.

Turning briefly to the upper arrangement (Fig. 9) we proceed as follows: The high frequency millivoltmeter, MV-18B, is connected through its crystal probe to a 10-megacycle sine-wave generator capable of delivering signals up to 30 volts. We make no attempt to calibrate either the generator voltage or the capacitive attenuators in the generator itself. Instead, a two-way switch enables us to connect a crystal rectifier alternatingly to the megacycle generator or to the 90-cycle generator. The 90-cycle generator, in turn, is monitored by a Weston dynamometer which we consider completely reliable, the more so since it is checked regularly against a standard cell. To simplify the diagram we have omitted the precision output divider of the 90-cycle generator, also a capacitive divider attached to the left section of the double throw switch. This divider keeps high level ac signals away from the crystal so that it cannot be damaged by overloading.

We calibrate our 10-megacycle signal by substituting a 90-cycle signal in the crystal rectifier circuit and adjusting the output of our 10-megacycle generator until the deflections of our MV-17B dc millivoltmeter are identical at 10 megacycles and 90 cycles per second. The advantage of this method is that we do not have to worry about changes in, or damages to, our crystal which could cause calibration errors. Neither do we care whether the MV-17B meter is accurately calibrated or not. As long as we have the same reference point on its dial we are certain that the amplitudes of the 90-cycle and the 10-megacycle signals are identical. Thus we transfer the reliable calibration of the Weston dynamometer to our 10-megacycle generator. The method is conclusive, if again we are sure of our wave shapes and that at 90 cycles and 10-megacycles there are no appreciable voltage drops in the crystal coupling condenser. To make sure that this condenser is large enough for the 90-cycle signal we use a 4-microfarad paper condenser. And to make sure that the same condenser does not create errors at 10 megacycles through inductivity or resonance we replace it by a 100-micromicrofarad mica condenser when switching from low to high frequency.

The checking equipment, Fig. 9 (bottom), uses the same 10-megacycle generator and an accurate capacitive divider. A vacuum diode, at the 30-volt level, rectifies and measures our output with a dc compensator, standard cell and MV-17B null-indicator. Because these two entirely different methods can be made to agree within one percent, we feel that our calibration is conclusive.

The frequency response of these meters above 30 megacycles follows the sloping curve already mentioned. It is checked by separate equipment.

XIII. CONCLUSION

Figure 10 shows the high frequency millivoltmeter which we calibrate as described. This is also the instrument which started us on the road of doubt and research which

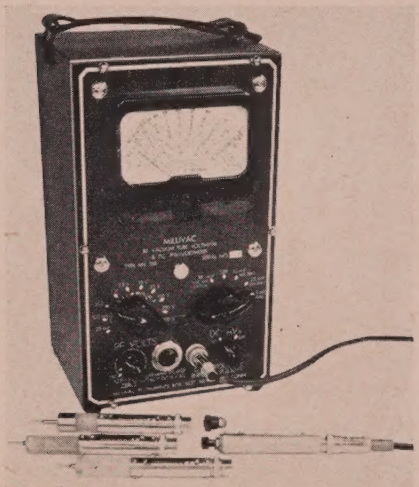


Fig. 10—High frequency millivoltmeter, 1 mc to 2,500 mc, 1 mv to 1,000 v.

led to the development of our own calibration methods and equipment. This road passes many unavoidable hazards but we feel that we have been able to understand the nature of these hazards and thus render them harmless. Thus we can calibrate high frequency meters with uncalibrated dc millivoltmeters and crystal diodes having "pitifully" warped voltage and frequency characteristics. We have isolated these weaknesses by methods and equipment resting on solid foundations, such as the standard cell, the dynamometer, low frequency resistance dividers, reliable capacitive dividers, perfect sine-wave generators, reliable equipment for analysis of wave shapes and the sound principle of "consistency."

Nothing in this world is perfect, including our calibration efforts, but we feel that at least we have evaluated most risks of error and that we know we are treading on safe ground. Our methods are certainly not the only conclusive ones. They are only examples of a philosophy which begins with doubt but does not exclude complete confidence, once true relationships have been established.

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